OPTICS

# Lasers Are Cool—and Cooling

## *Breakthrough laser-driven crystal cryocooler with no moving parts*

Compared to heating, cooling is notoriously difficult and inefficient. It typically involves compressing and circulating a specialized refrigerant that draws heat away from one region and dumps it somewhere else (e.g., behind the fridge). The whole endeavor remains curiously old-fashioned, with all the groaning noise and rattling vibration one might expect from a process that essentially operates by 19$^{th}$ century plumbing.

However, in cutting-edge laboratory science, or in remote locations, such as onboard a spacecraft, rumbling plumbing just won't cut it: the noise and vibration interfere with sensitive systems. Even in the most advanced cryocoolers, moving parts remain a significant drawback. Now, for the first time, moving parts are no longer necessary.

A research collaboration between Los Alamos and the University of New Mexico, led by Los Alamos scientist Markus Hehlen, recently unveiled a breakthrough in cooling technology: an all-solid-state optical cryocooler with no moving parts. While not cost effective for everyday consumer refrigeration, the new system offers tremendous benefit for advanced imaging and other applications.

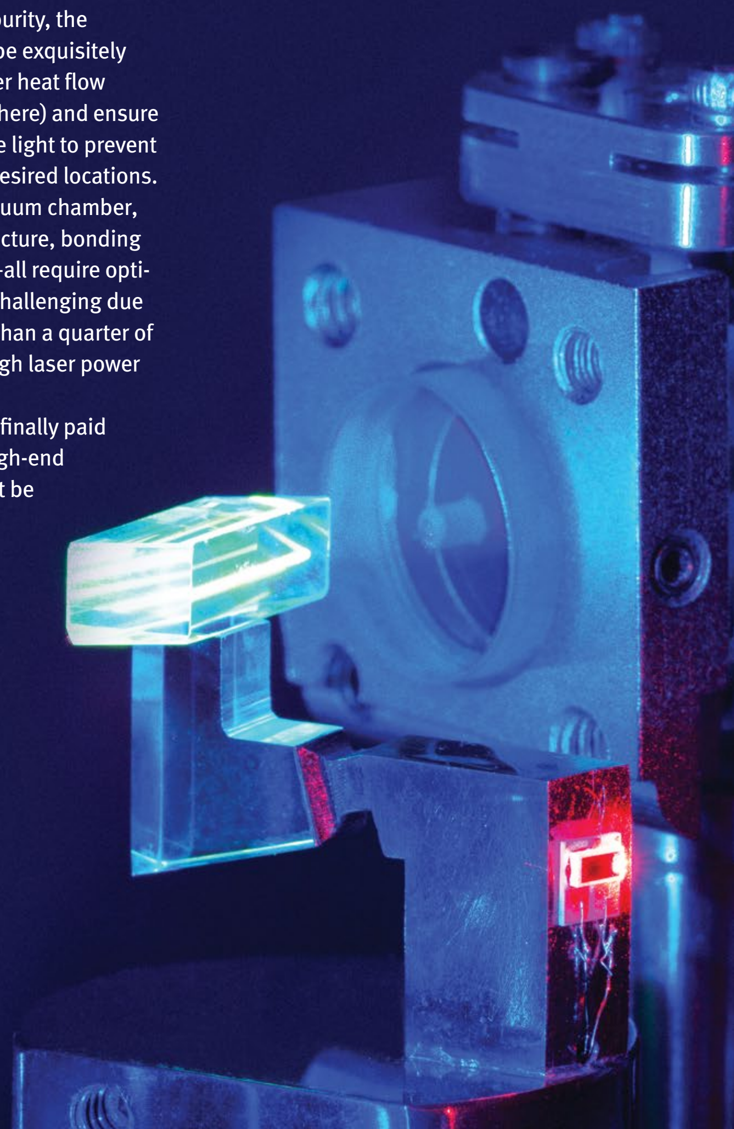
The cryocooler takes advantage of anti-Stokes fluorescence, in which a material emits light at a slightly higher average energy than that of an exciting laser. To make up the difference, energy is withdrawn from heat within the material; it is essentially a laser running in reverse. Net cooling of a solid by anti-Stokes fluorescence was first observed in Los Alamos, in 1995.

Even though it was observed decades ago, using anti-Stokes fluorescence to create a practical cryocooling system has proven exceedingly difficult, requiring a combined absorption and quantum efficiency of 98 percent or more. That means the fluorescing material must be an extraordinarily pure crystal. The team was able to achieve this with an yttrium-lithium-fluoride ($YLiF_4$) crystal, in which about 10 percent of the yttrium ions ($Y^{3+}$) were replaced (or "doped") with ytterbium ions ($Yb^{3+}$). It is these $Yb^{3+}$ ions that emit anti-Stokes fluorescence when excited by a laser at a 1020-nm wavelength, in the near infrared.

In addition to the crystal purity, the surrounding apparatus must be exquisitely designed to achieve the proper heat flow (conducting here, insulating there) and ensure the escape of the fluorescence light to prevent it from generating heat in undesired locations. The various components—vacuum chamber, mirrors, sensors, support structure, bonding agents, and optical coatings—all require optimization. This is particularly challenging due to the small crystal size (less than a quarter of a cubic centimeter) and the high laser power (50 watts or more) involved.

All that attention to detail finally paid off when the team cooled a high-end infrared sensor, such as might be used on a telescope or a thermal-imaging satellite, to its desired operating temperature of –138 degrees Celsius, much colder than existing nonmechanical cryocoolers can handle. A big part of that success relied upon designing a specialized thermal link to attach the sensor to the cooling crystal without creating an insulating barrier between them or allowing the crystal's fluorescence to warm the sensor. (An adhesive mounting, for instance, would have failed on both counts.)

The research, which capitalized on a number of key Los Alamos specialties (such as optical technologies, crystal growth, and aerogels) and facilities (Target Fabrication Facility, Center for Integrated Nanotechnology, and advanced clean rooms), may prove transformative for a number of high-tech applications. For example, by eliminating mechanical jitter, the optical cryocooler could greatly improve image quality from



Experimental setup with cooling crystal (green) atop a specially designed L-shaped thermal link that draws heat from an infrared sensor (red) and its mounting, cooling the sensor to its operational temperature of –138 degrees Celsius. The crystal is being excited by an infrared laser beam and cools by fluorescing at a slightly higher infrared energy (both unseen); the green glow, which produces negligible heating, is due to an unrelated excitation of the element erbium, an impurity within the crystal. *PHOTO CREDIT: Alexander Albrecht/UNM* ground- and space-based telescopes and high-magnification cryogenic electron microscopes without the need for ancillary systems to compensate for vibration. It also stands to upgrade a number of non-imaging applications, from improving the resolution of gamma-ray detectors to tightening the accuracy of atomic clocks.

Laser-driven crystal cooling can even revolutionize the laser itself. Upon demonstrating the new cryocooler, Hehlen and external collaborators immediately set to work on an important application: a self-cooling laser, in which the heat generated by the laser is exactly offset by the heat carried away by its own laser-crystal cooling. By eliminating thermal instabilities, such "radiation-balanced" lasers will be able to operate at much higher power. Cool. LDRD

*—Craig Tyler*

THREAT DETECTION

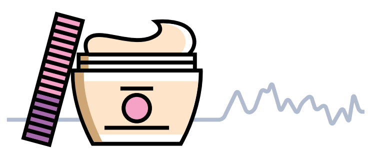
# Security Through Signatures

## *Identifying chemicals through their atomic-level interactions*

Some dangers are easily hidden in plain sight. Consider an unlabeled three-ounce bottle of clear liquid: it could be water, it could be rubbing alcohol, or it could be something more hazardous. Is it safe to be shipped through the mail? Or taken aboard an airplane? Certain chemicals can be toxic if released into the air, so somehow the bottle's contents need to be verified without removing the lid. Although current detection techniques are doing the job, recent advances in identifying chemicals by studying their atomic interactions could usher in a new level of scrutiny.

In 2010, Los Alamos physicist Michelle Espy and her team made headlines when they introduced a method of scanning travel bottles for liquid explosives using ultralow-field nuclear magnetic resonance (ULF-NMR). Nuclear magnetic resonance can be used to characterize atoms in molecules by measuring the response of their nuclei to a magnetic field. Although the two-step process was ultimately too slow for the impatient passenger queues at airport security, the team was onto something: small, portable, low-field magnets can be useful for detecting specific chemical compounds, and sometimes they can be even more useful than their high-field cousins.

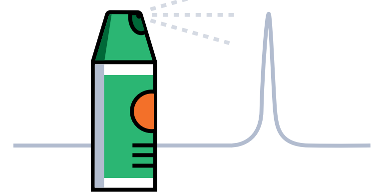
In traditional NMR, strong magnetic fields cause the nuclei of atoms to align with the field. Then, a weaker oscillating magnetic field is applied to search for a resonant response from the nuclei, which occurs at an oscillation frequency that's specific to the material being probed. Varying the strength of the primary (static) magnetic field can cause the nuclei to resonate at different frequencies depending on their exact chemical environment—a phenomenon referred to as chemical shift.



These patterns of resonances can be used to identify the atoms in chemical compounds, but at very low magnetic fields, the chemical shift disappears and the signals get lumped together in a very narrow frequency range. However, upon closer examination, Espy and colleague Bob Williams discovered that for some compounds, the frequency signals are actually quite distinctive.

"We found that molecules containing a few specific elements have a unique fingerprint," says Espy. And the fingerprints they discovered are especially helpful. Using fertilizers, insecticides, and related materials as surrogates, Espy, Williams, and their colleagues have used ULF-NMR to rapidly (less than 8 seconds) identify the fingerprints of chemical-threat agents in TSA-approved travel bottles, as part of a project supported by the Department of Homeland Security's Science and Technology Directorate through an interagency agreement with Los Alamos.

These characteristic signals are caused by a phenomenon referred to as J-coupling, which happens when the nuclei of neighboring atoms in molecules begin to interact, or couple, with each other when the magnetic field is applied. For instance, one may expect a compound containing two hydrogen-carbon bonds to show two distinct hydrogen signal peaks, but if they are coupled, the peaks will instead split into four smaller ones. What's fascinating is that although high magnetic

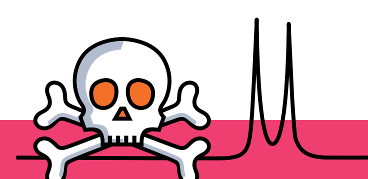


fields can detect these unique J-coupled signatures, they are much richer at very low field—in fact, the lower the better.

"Using advanced electronics that are now available, we are able to see these interactions using only the earth's 50-microtesla magnetic field," says Williams, a bio-organic chemist. (A magnetic field of 50 microteslas is tens of thousands of times weaker than that used by a typical medical MRI machine.)

Williams explains that although J-coupling has been used for many years to determine chemical structures, it has never before been done with magnetic fields this low. Low fields mean smaller magnets and the potential for a whole new level of portable chemical detection. LDRD

*—Rebecca McDonald*



When chemical compounds are exposed to ultralow magnetic fields, the nuclei of specific elements can interact, causing the signal to split in a unique way. This phenomenon, called J-coupling, is being used to identify chemicals of interest.